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# HIGH-TEMPERATURE TRANSIENT PRESSURE TRANSDUCER FOR USE IN LIQUID-METAL SYSTEMS

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16. Abstract

The design and testing of a high-temperature transient pressure transducer is described. It is capable of operating at 1090 K (1500$^\circ$ F) in the presence of a liquid metal. The range of the transducer is 0 to 69 N/cm$^2$ (0 to 100 psi) with a useful response to 200 Hz. Sensitivity of the transducer is 8 pC/(N)(cm$^2$) (5.5 pC/psi). Two transducers were tested at 1090 K (1500$^\circ$ F) for greater than 1100 hr.

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# HIGH-TEMPERATURE TRANSIENT PRESSURE TRANSDUCER FOR USE IN LIQUID-METAL SYSTEMS

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## SUMMARY

A pressure transducer was designed to measure transient pressures at high temperatures in liquid-metal systems. A small bellows was used as the sensing element and a miniature quartz load cell for mechanical-to-electrical conversion. Because of the characteristics of piezoelectric load cells and charge amplifier characteristics, the transducer was not capable of making long-term steady-state pressure measurements. Usable frequency response to 200 hertz was indicated on the basis of a natural resonance of 2500 hertz and the measured volumetric stiffness of the transducer. However, piping used to connect the transducer into a system may reduce the usable response range. Tests were conducted on two transducers with a range of 0 to 69 newtons per square centimeter (0 to 100 psi). One was tested in a hot gas furnace and the other in a liquid-metal facility. The transducers had pressure sensitivities of about 8 picocoulombs per newton per square centimeter (5.5 pC/psi), a shift in sensitivity due to a temperature change of about 3 percent per 1000 K ($1800^\circ$ F), a change in sensitivity with time while at 1090 K ($1500^\circ$ F) of about -0.5 percent per 1000 hours, and an acceleration sensitivity of 0.6 percent full scale per g. The combined effect of nonlinearity and hysteresis was less than 0.3 percent full scale. This value was also the estimated uncertainty in test instrumentation.

## INTRODUCTION

Recent efforts to develop Rankine cycle space power systems have created new requirements for instrumentation. These requirements include the necessity for long-term reliability while operating in the high-temperature corrosive environment of liquid-metal systems. The pressure measurement systems that meet these requirements are severely limited in frequency response. Therefore, Lewis Research Center undertook to develop and test a transient pressure transducer designed for liquid-metal applications. This report is a summary of that program.

Several areas of study growing out of the Rankine cycle space power development program need transient pressure data. For example, in the study of boiling and condensing phenomena, pressure fluctuations must be known to determine local heat-transfer coefficients. Another example is that transient measurements are needed in boiler instability studies. Also, in the design of automatic controls for Rankine cycle power systems, the transient behavior must be measured so that overall system stability can be ensured. Obviously, the frequency range of interest varies with the experiment, but in many cases, a transducer system capable of reliable operation with a flat response to 200 hertz is sufficient.

To date, pressure measurements have been made with systems designed basically for steady-state measurements. Limp diaphragm transducers (ref. 1), inert gas efflux techniques (ref. 2), and commercial strain-gage transducers connected to the system by liquid legs have been used for most pressure measurements. The usable frequency response of these systems is generally limited to less than a few hertz. Thus, a need exists for a transducer that would extend the responses from a hertz to a few hundred hertz.

The design goals chosen for the transducer development program reported herein are a pressure range of 0 to 69 newtons per square centimeter (0 to 100 psi), a frequency response to at least 200 hertz, compatibility with liquid sodium for at least 1000 hours at 1090 K ($1500^{\circ}$ F), and an overall probable error of less than 3 percent. These goals would allow for close coupling of the transducer to the liquid-metal system, which would reduce the dynamic effects caused by the pressure transmission system. These goals represented an advancement in the state of the art of pressure measurement in liquid-metal systems and were to be achieved solely by the use of available materials and components. The transducer should be designed so that, as new materials become available, its operating temperature and pressure range could be extended while the same basic design was used. In the following sections, the transducer design is discussed, a summary of the tests performed to prove the soundness of the design is given, and a summary of operating characteristics is given.

## TRANSDUCER DESIGN

Three ideas entered into the design of this transducer: (1) it should be made as stiff as possible to achieve a high mechanical natural frequency, (2) the sensing element should be capable of operating at 1090 K ($1500^{\circ}$ F) so that the transducer could be close coupled to the liquid-metal system to minimize the dynamic effects of the pressure transmission system, and (3) the mechanical-to-electrical conversion device should operate in a thermal environment that ensures reliable long-term stability.

A schematic diagram of the transducer is shown in figure 1. The sensing element consists of an end cap and bellows. The bellows act basically as a seal in the transducer. This sensing element converts the unknown pressure into a force that is transmitted to a miniature quartz load cell by way of the inner tube. The load cell is rigidly supported from the system piping by the outer housing. The transducer was designed to have an output sensitivity of approximately 8.0 picocoulombs per newton per square centimeter (5.5 pC/psi). This output was achieved by using a sensing element with an effective area of 0.81 square centimeters (0.11 in.$^2$) and a load cell with a sensitivity of approximately 11.2 picocoulombs per newton (50 pC/lbf).

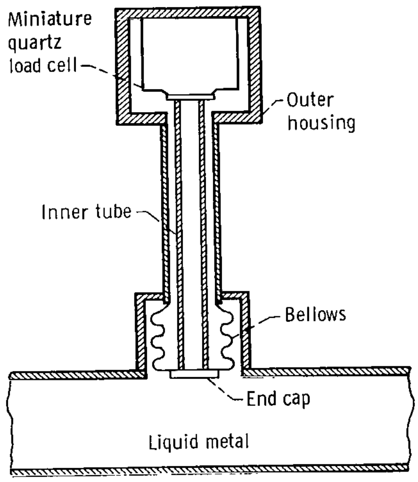



Figure 1. - Schematic diagram of transducer.

The overall size of the transducer was dictated by the following considerations: First, since the temperature limitation of the load cell was 422 K (300° F), the transducer had to be long enough to ensure a 666 K (1200° F) temperature difference between the bellows and load cell. Second, the sensitivity of the load cell along with the required pressure range and signal-to-noise ratio determined the effective area requirement of the sensing element. Third, the mechanical resonance had to be high with respect to the highest frequencies to be measured, which dictated that the mechanical natural frequency be greater than 2000 hertz. This response is achieved if the transducer is made as stiff as possible and has a negligible moving mass. Fourth, the transducer had to be as small as possible since for many applications, system piping is generally less than 2 centimeters (0.79 in.) in diameter.

A detailed drawing of the transducer is shown in figure 2. The sensing bellows is made of Inconel X (750) and is welded closed with an end cap also made of Inconel X

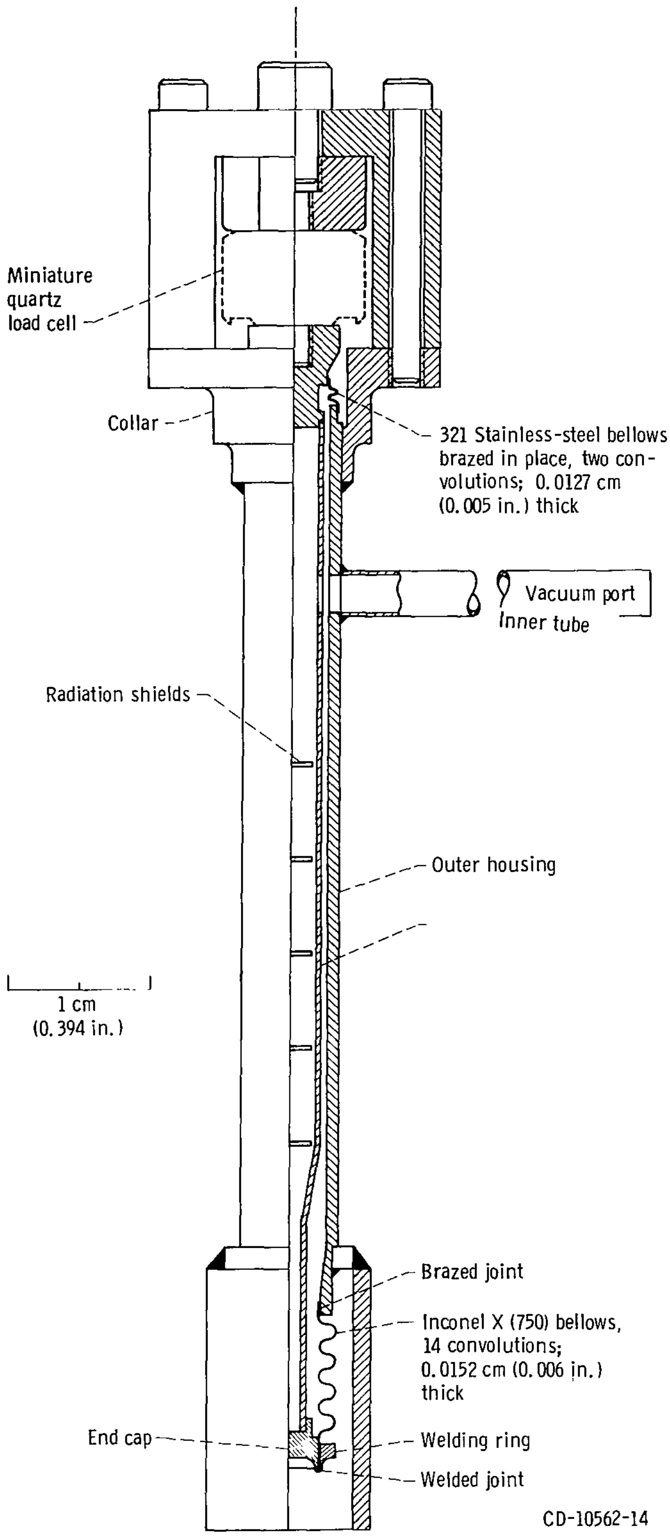



Figure 2. - Detailed drawing of transducer.

(750). The other end of the bellows is furnace brazed to the outer housing. (Ref. 3 describes a program that involved testing of brazing alloys for compatibility with sodium.) A second seal is achieved by using a bellows with two convolutions that is located at the load cell end. This bellows is made of 321 stainless steel and is also brazed in place. The outer housing, inner tube, and other welded assemblies are made of 316 stainless steel. The remaining parts that do not require welding are made of 304 stainless steel. When in use, the inside of the transducer is evacuated to reduce heat conduction along its length. Thermal radiation is reduced by placing spring-loaded metal disks along the transducer length inside the inner tube. When the load cell is mounted, both surfaces are subjected to a torque of 2.25 newton-meters (20 in.-lb), following the manufacturer's specifications. A partially complete and also a complete transducer are shown in figure 3. Engineering drawings of this transducer are available on request to the author at the Lewis Research Center (refer to drawing number CF-235091).

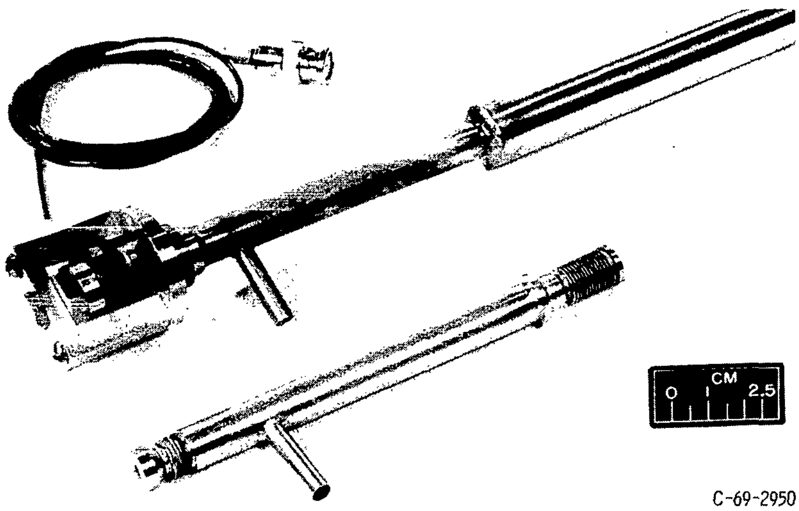



Figure 3. - Transducer in two stages of construction.

This transducer design has two features that are particularly advantageous for liquid-metal system applications: (1) a double seal between the liquid metal and the outside environment and (2) a load cell that can be removed and replaced without breaking into the liquid-metal system piping.

## Signal Conditioning Effects

The use of a piezoelectric load cell and either a charge or voltage amplifier does not allow long-term steady-state measurements to be made. The reason is that the piezoelectric crystal is a device which generates charge only when a change in stress occurs. The amplifiers measure either the charge or the voltage developed across a known capacitor. Either amplifier has a characteristic time constant associated with its operation which limits its low frequency response. The time constant is a function of amplifier settings and can range from less than $10^{-2}$ to $10^{6}$ seconds. Thus, by use of long time constants, quasi-steady-state measurements are possible. In the calibration tests described herein, a charge amplifier was used with a time constant of $10^{5}$ seconds. Since a calibration required about 6 minutes, errors of 0.3 percent full scale at the most could result from this effect. If the design were to be modified and a strain-gage type load cell used, steady-state measurements might be made, but temperature effects that are discussed in the next section may become a problem. Also, the mechanical natural frequency would be lowered because the stiffness of a strain-gage load cell would be less than that of the quartz load cell.

## Thermal Effects

The sensitivity of the transducer varies with operating temperature. Primary contributors to this change are thermal expansion of the sensing element and the change in sensitivity of the load cell with temperature. On the basis of a mean thermal expansion coefficient of $16.7 \times 10^{-6}$ centimeter per centimeter per K ($9.3 \times 10^{-6}$ in./(in.)($^{\circ}$F)) (ref. 4), the sensitivity of the transducer would be expected to increase 3.34 percent per 1000 K (1.86 percent/1000$^{\circ}$ F) because of changes in the effective area of the sensing element. Tests indicated that the sensitivity of the load cell decreased by 8 percent per 1000 K (4.4 percent/1000$^{\circ}$ F), which, in turn, would effect a decrease in transducer sensitivity. In operation, the load cell temperature changed about 100 K (180$^{\circ}$ F), which would result in an 0.8-percent decrease in sensitivity. Also, the modulus of elasticity of the materials used in transducer construction decreases with temperature and would cause the transducer sensitivity to decrease. Because of the complexity of the transducer structure, a quantitative estimate of these combined effects is not possible. Experimental values are given in the sections on transducer testing.

In operation, the transducer output normally varied under a steady-state (constant pressure and what is assumed to be a constant temperature) condition. This variation is caused by changes in the relative lengths of the inner and outer tubes due to variations in the heat loss rate from the outer tube. The convective heat transfer was stabilized by placing a stainless-steel shield around the transducer. Even with this shield, the output under steady-state conditions still tended to drift. The amount of drift occurring in the transducer output is dependent on amplifier time constant settings. A tracing of the recorded output from a typical transducer operating under steady-state conditions at

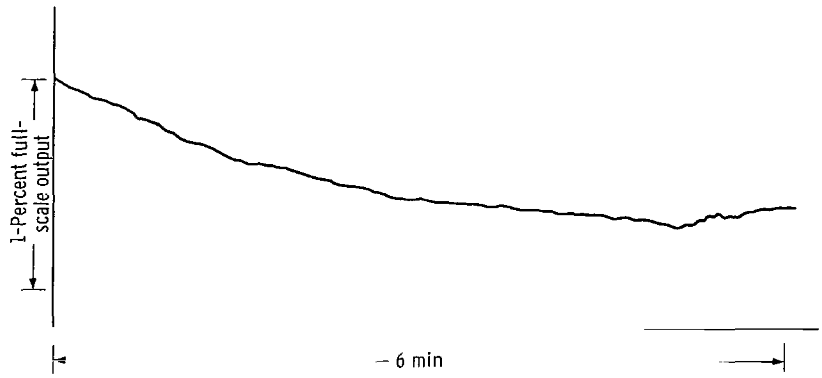


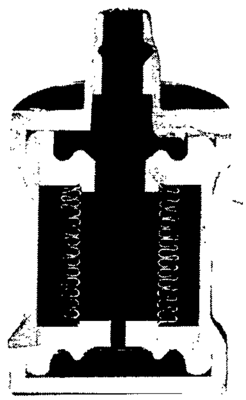

Figure 4. - Thermal drift of transducer operating at 1090 K (1500° F) under steady-state conditions (charge amplifier time constant set at $10^6$ sec).

1090 K (1500° F) is shown in figure 4. The charge amplifier was set at zero before the recording was made. As indicated, the variation in output is less than 1 percent over a 6-minute interval. For shorter time constant settings, less drift would appear in the output. Thus, for the measurement of transient pressure for which shorter time constants would be used, negligible error would be introduced. It should be realized that any changes in temperature of the operating environment, which the transducer may "see," will introduce variations in the output also.

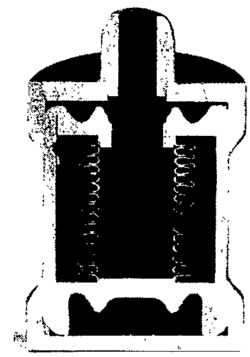
## Sensing Bellows Selection

Ideally, sensing bellows should have a very low stiffness, mainly to reduce the thermal effects. This low stiffness requires the use of a bellows with thin walls, which introduces the problem of creep due to high stress levels, high temperature, and long periods of operation. This creep problem was borne out in the testing of some early transducers, the pressure sensitivities of which decreased significantly under these conditions. Examination of these transducers showed that their sensing bellows had collapsed. Since the effects of creep cannot be easily predicted, a set of bellows capsules was constructed and tested to determine which commercially available bellows would meet the time, temperature, and pressure goals. Candidate bellows of the proper size and wall thicknesses, made from 321 stainless steel and Inconel X (750), were tested. Cross sections of five of these capsules are shown in figure 5. The specifications for these bellows are listed in table I.

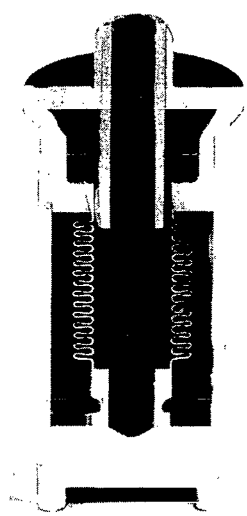
Since the bellows in this application is basically a seal and does not receive any severe flexing, the capsules were designed to maintain the bellows length fixed. Some of the capsules had the Inconel X bellows brazed in place whereas others were com-



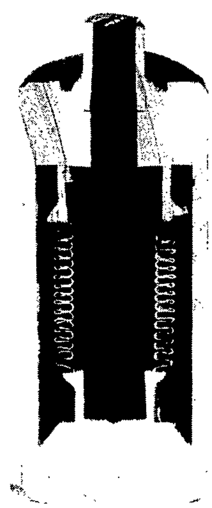
(a) Inconel X (750) welded construction after 4442 hours at 1090 K (1500° F) and 69 newtons per square centimeter (100 psid).



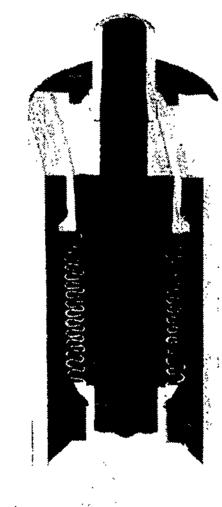
(b) Inconel X (750) welded construction after 4348 hours at 1090 K (1500° F) and 86 newtons per square centimeter (125 psid).



(c) Inconel X (750) brazed construction after 4130 hours at 1090 K (1500° F) and 69 newtons per square centimeter (100 psid).



(d) 321 Stainless steel welded construction after 1676 hours at 978 K (1300° F) and 41 newtons per square centimeter (60 psid).



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(e) 321 Stainless steel welded construction after 1723 hours at 1090 K (1500 F) and 17 newtons per square centimeter (25 psid).

Figure 5. Bellows test capsules after test.

TABLE I. - SENSING BELLOWS SPECIFICATIONS

| Specification | Inconel X (750) | 312 Stainless steel |
|---|---|---|
| Inside diameter, cm (in.) | 0.772 (0.304) | 0.812 (0.320) |
| Outside diameter, cm (in.) | 1.203 (0.474) | 1.191 (0.469) |
| Thickness, cm (in.) | 0.015 (0.006) | 0.011 (0.0045) |
| Length, cm (in.) | 1.52 (0.6) | 1.752 (0.69) |
| Number of convolutions | 14 | 15 |

pletely welded. In all cases, the Inconel X was fully heat treated. The capsules were suspended in furnaces at temperatures and pressures indicated in figure 5. The pressure was applied to the outside of the bellows through a port not shown in the figure. Periodically, the capsules were removed and X-rayed. Failure was assumed to occur when the convolutions appeared to collapse (e.g., see the stainless-steel bellows of fig. 5(d)). As a result of these tests, the Inconel X bellows was chosen for the transducer. It should be pointed out that in no cases did any of the bellows from this series of tests develop leaks detectable with a helium mass-spectrometer leak detector.

## Mechanical Vibration Effects

From a dynamics standpoint, the transducer is a complex mechanical system. Approximate estimates based on a simple spring mass system placed the first resonance at beyond 3000 hertz. This calculation was checked by measuring the first resonant frequency of the transducer by exciting it on an electromagnet shaker. Constant acceleration levels were applied axially to the transducer as the frequency was swept from 40 to 5000 hertz. A typical curve of root-mean-square output as a function of frequency for various acceleration levels is shown in figure 6. The first major resonance occurs at 2500 hertz. The acceleration sensitivity of the transducer is 0.65 percent full scale per g for frequencies less than 400 hertz. This value is much larger than the typical one of 0.02 percent full scale per g quoted for most strain-gage pressure transducers. Therefore, a user must be careful in interpreting the transducer output when operating in an installation where vibration levels are high.

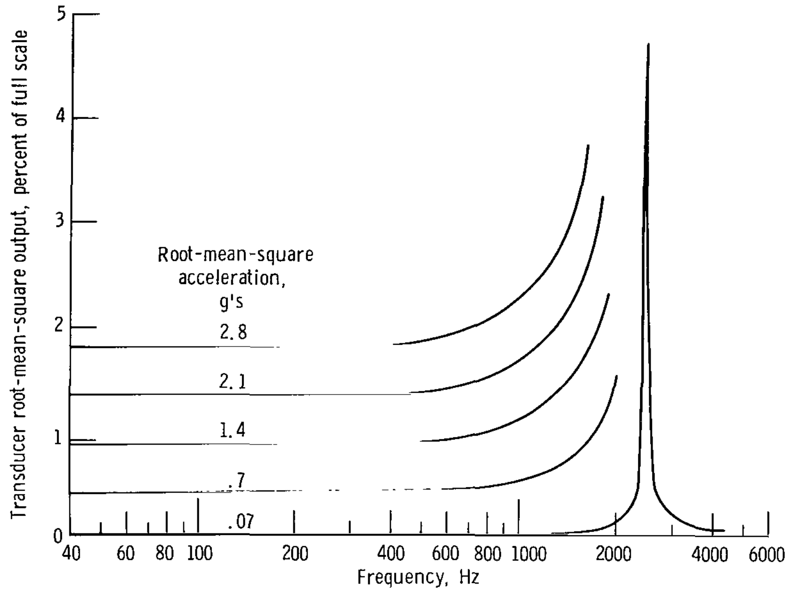


Figure 6. - Vibration response of transducer (acceleration of 1 g = 980.1 cm/sec$^2$ or 32.2 ft/sec$^2$).

Therefore, a user must be careful in interpreting the transducer output when operating in an installation where vibration levels are high.

## Transducer Frequency Response

Except for a flush-mounted transducer, the frequency response of a pressure measuring system is limited by the pressure transmission system dynamics. Transducer parameters that affect system dynamics include the transducer mechanical natural frequency and volumetric stiffness. Tests indicate that the transducer volumetric stiffness is in the range of $3.6\times10^{-5}$ cubic centimeter per newton per square centimeter ($1.5\times10^{-6}$ in.$^3$/psi). This value compares with $2.4\times10^{-5}$ cubic centimeter per newton per square centimeter ($1.0\times10^{-6}$ in.$^3$/psi) for a typical stiff strain-gage transducer. Equation (6.74) from reference 5 relates the system dynamics to measurable system parameters:

$$f_n = \frac{1}{2\pi}\left(\frac{1}{\omega^2} + \frac{16\rho LC}{3\pi d^2}\right)^{-1/2}$$

where

$f_n$ natural resonant frequency of system, Hz

$\omega$ transducer mechanical natural frequency, rad/sec

$\rho$ fluid density, $kg/cm^3$; $slug/in.^3$

L connecting tube length, cm; in.

C transducer volumetric stiffness, $cm^3/(N)(cm^2)$; $in.^3/psi$

d connecting tube diameter, cm; in.

To illustrate what a typical system response would be when the transducer is used. consider sodium at 1090 K ($1500^\circ$ F) as the working fluid with a density of $7.54\times10^{-4}$ kilogram per cubic centimeter ($8.47\times10^{-4}$ $slug/in.^3$) and a connecting tube with a length of 7.6 centimeters (3 in.) and a diameter of 0.64 centimeter (0.25 in.). For this system, the calculated natural frequency is 1403 hertz. Since this is a lightly damped second-order system, usable response to 240 hertz can be obtained if data with less than 3 percent error are desired. Thus, even with some connecting tubing, the transducer is capable of meeting the frequency response design goal, provided that the transducer is completely filled with liquid.

## TEST RESULTS

Two transducers were tested at temperatures up to 1090 K ($1500^\circ$ F) for times exceeding 1000 hours. One transducer was tested in a furnace with argon used as the pressurizing gas. The other transducer was mounted in a liquid-metal instrument test facility that used sodium as the pressurizing fluid. During both the hot gas and the liquid-metal tests, the transducer temperature was controlled to ±5 K (±$9^\circ$ F). A digital voltmeter accurate to ±0.2 percent was used to read the output from the charge amplifier. Periodic calibration of the charge amplifier showed a gain stability of ±0.1 percent. The pressure applied to the transducer was read from a bourdon tube pressure gage with an accuracy of ±0.2 percent full scale. With this instrumentation, an uncertainty of ±0.3 percent full scale could be expected in a reading based on the square root of the sum of errors squared. For a span or sensitivity measurement as defined in a following section, uncertainties of less than ±0.5 percent could be expected from the instrumentation.

At each test condition, two 11-point calibrations were made that consisted of measuring the output at intervals of 14 newtons per square centimeter (20 psi) while going from 10 to 79 and back to 10 newtons per square centimeter absolute (15 to 115 to 15 psia). In general, for all tests the nonlinearity and hysteresis values were less than the uncertainty in the measured values. Where exceptions occurred, they could be traced to thermal drift in the transducer.

In the following sections, test results are given in terms of percentage change in sensitivity from the initial sensitivity. Sensitivity is defined as the difference between the average zero and the full-scale readings divided by the change in pressure between zero and full scale.

## Hot Gas Test

A transducer was welded into a 20-centimeter (8-in.) length of schedule 40 pipe and held vertically while being tested. The pipe, transducer base, and the gas supply tubing were heated with an electric heater. Thermal insulation was wrapped over the heater, pipe, and tubing. A thermocouple, used for temperature measurement and control, was spot welded to the outside of the pipe in the vicinity of the brazed joint on the sensing bellows. A second thermocouple was welded to the transducer on the collar (see fig. 2) to measure approximate load cell temperature. The test was run in a room where the temperature was held at 298 K (75° F). The normal operating temperatures for this environment are listed in table II. A vacuum of less than 20 microns was maintained inside the transducer. An aluminum cap was placed over the load cell section of the transducer to stabilize the heat transfer. A quiescent pressure of 69 newtons per square centimeter absolute (100 psia) was maintained on the transducer at all times except when calibrations were made. The temperature time schedule followed during the test is shown in figure 7. A total of 1150 hours was logged at 1090 K (1500° F) or above, 120 hours at 810 K (1000° F), and 144 hours at 533 K (500° F) before the test was terminated.

The effects of test time and temperature on the sensitivity of the transducer as measured in the hot gas test are shown in figure 8. Over the first 1000 hours of the test, the sensitivity decreased at a rate of 0.5 percent per 1000 hours. This rate was determined from a least-squares fit of the data by assuming that each set of data points for a given temperature had the same slope. In the authors' opinion, the shift in sensitivity with time is caused by creep in the sensing bellows. As the convolutions change shape, the effective area may decrease, which would result in a decrease in sensitivity. The initial sensitivity of the transducer at 298 K (75° F) was 8.18 picocoulombs per newton per square centimeter (5.63 pC/psi).

The sensitivity shift with temperature was evaluated by plotting the intercept points of the three curves in figure 8, as shown in figure 9. The slope of these points in the region from 530 to 1090 K (500° to 1500° F) reveals a change in sensitivity with temper-

TABLE II. - TRANSDUCER OPERATING TEMPERATURES

| Test temperature | | Test | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Hot gas | | | | Liquid metal | | | |
| | | Environment | | Collar | | Environment | | Collar | |
| | | Operating temperature | | | | | | | |
| K | °F | K | °F | K | °F | K | °F | K | °F |
| 1090 | 1500 | 298 | 75 | 400 | 260 | 336 | 145 | 414 | 285 |
| 810 | 1000 | 298 | 75 | 361 | 190 | 331 | 135 | 375 | 215 |
| 533 | 500 | 298 | 75 | 322 | 120 | 316 | 110 | 341 | 155 |

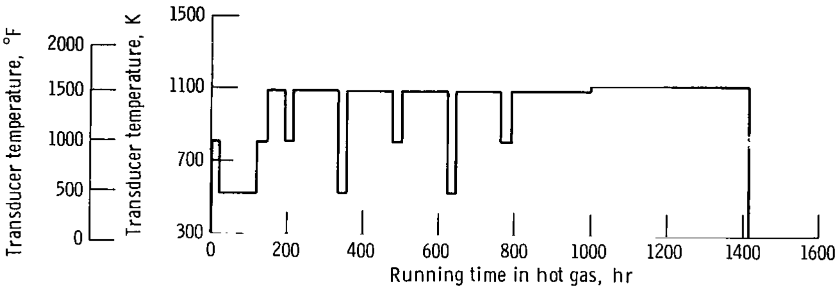


Figure 7. - Transducer schedule for hot gas test.

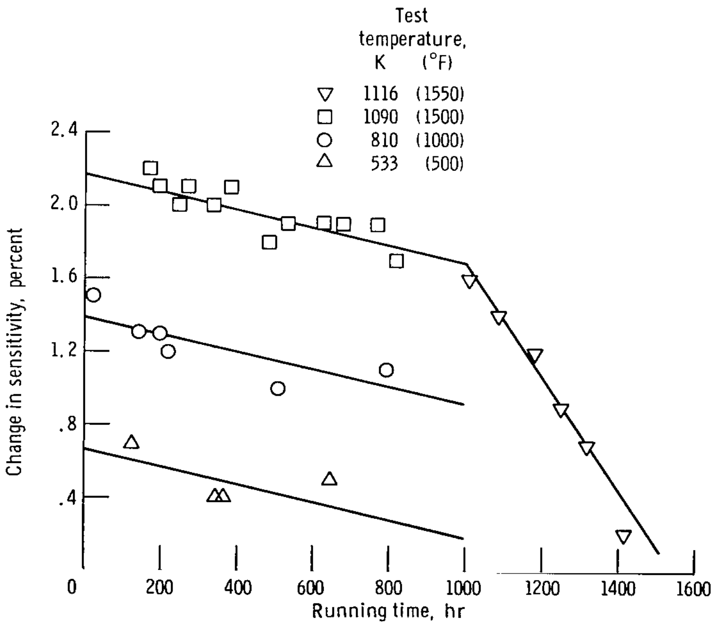


Figure 8. - Summary of calibrations from hot gas test.

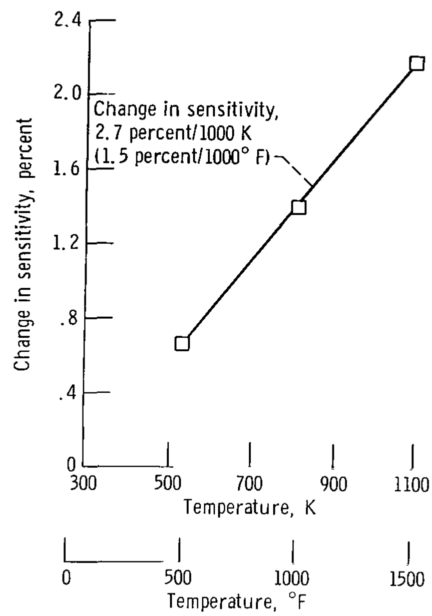


Figure 9. - Change in sensitivity as function of temperature for hot gas test.

ature of 2.7 percent per 1000 K (1.5 percent/1000° F). This value compares with that of 0.018 percent per K (0.01 percent/°F) considered standard for a commercial strain-gage pressure transducer.

At the 1000-hour point (fig. 8), an adjustment in the control set-point temperature was made to offset what appeared to be a low operating temperature. Later, this low temperature proved to be caused by a change in the controller calibration, and thus the operating temperature was greater than 1118 K (1550° F). Because of this higher operating temperature, the creep rate in the bellows increased, thereby causing the rate of change in sensitivity to increase. Thus, for this transducer, 1090 K (1500° F) represents a reasonable upper limit of operating temperature if the transducer is to be used for long time periods.

## Liquid-Metal Test

A second transducer was mounted on a test leg of the liquid-metal instrument test facility. This facility consists of a tank that can be filled with liquid sodium, heated to as high as 1090 K (1500° F), and pressurized with argon gas to as high as 103 newtons per square centimeter absolute (150 psia). The transducer installed on the test leg is shown in figure 10. Electrical heaters were wrapped around the base of the transducer. Thermocouples were attached to the base and collar areas of the transducer. The test

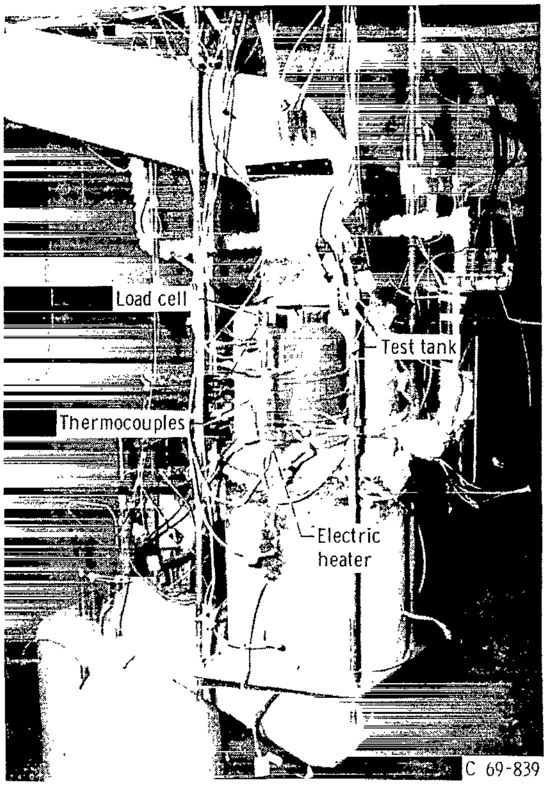

Figure 10. - Transducer mounted in liquid-metal test facility.

tank is operated in a steel enclosure. The normal operating temperatures of the transducer are listed in table II. The air temperature in the enclosure is listed as the environment temperature in the table. The test tank and test leg were filled with sodium while under vacuum. Figure 11 shows the transducer as it was tested with thermal insulation in place, an aluminum cap covering the load cell, and the stainless-steel shield surrounding the lower section. A vacuum of less than 20 microns was maintained inside the transducer. During this test, the quiescent pressure level was 17 newtons per square centimeter absolute (25 psia). The test schedule followed is shown in figure 12. The following total hours of testing were logged at the specified temperatures: 1180 at 1090 K ($1500^{\circ}$ F), 430 at 810 K ($1000^{\circ}$ F), and 168 at 533 K ($500^{\circ}$ F). Also shown in figure 12 are the points at which the facility test tank was emptied and filled with sodium.

The effects of test time and temperature on the sensitivity of the transducer as measured in the liquid-metal test are shown in figure 13. Based on the computation method described for the hot gas test, the changes in sensitivity with time amounted to -0.4 percent per 1000 hours. The initial sensitivity of this transducer measured before sodium was introduced into the test tank was 8.14 picocoulombs per newton per square centimeter (5.61 pC/psi). Figure 14 shows the intercept data that were used to determine the

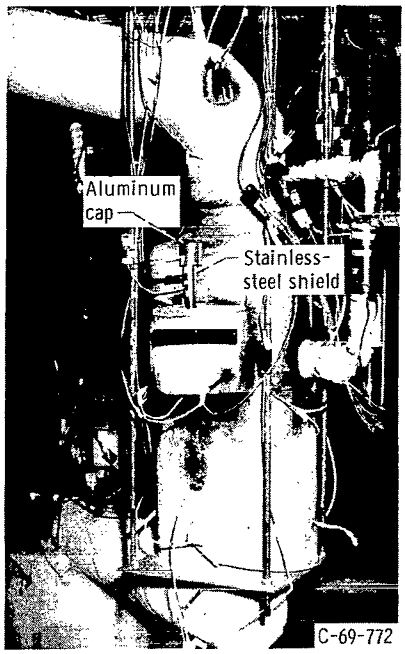


Figure 11. - Transducer fully insulated in liquid-metal test facility.

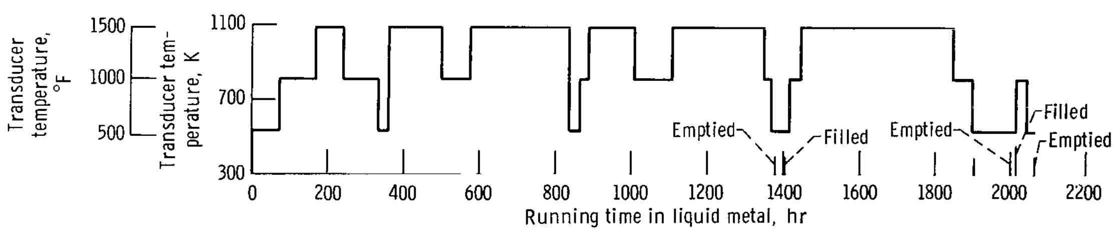


Figure 12. - Transducer schedule for liquid-metal test.

temperature sensitivity plotted as a function of temperature. The extension of the curve would be expected to pass through the horizontal axis near the 300 K ($80^{\circ}$ F) point. However, the vertical position is a function of the initial sensitivity used to normalize the data in figure 13. An error of 0.5 percent in the initial sensitivity could have resulted in the downward shift, as shown in the figure. Since the normalizing factor does not affect the slope of the curve, the average change in sensitivity of this transducer in the temperature range of 530 to 1090 K ($500^{\circ}$ to $1500^{\circ}$ F) is 2.5 percent per 1000 K (1.4 percent/$1000^{\circ}$ F). This value agrees well with the 2.7 percent per 1000 K (1.5 percent/$1000^{\circ}$ F) measured in the hot gas test.

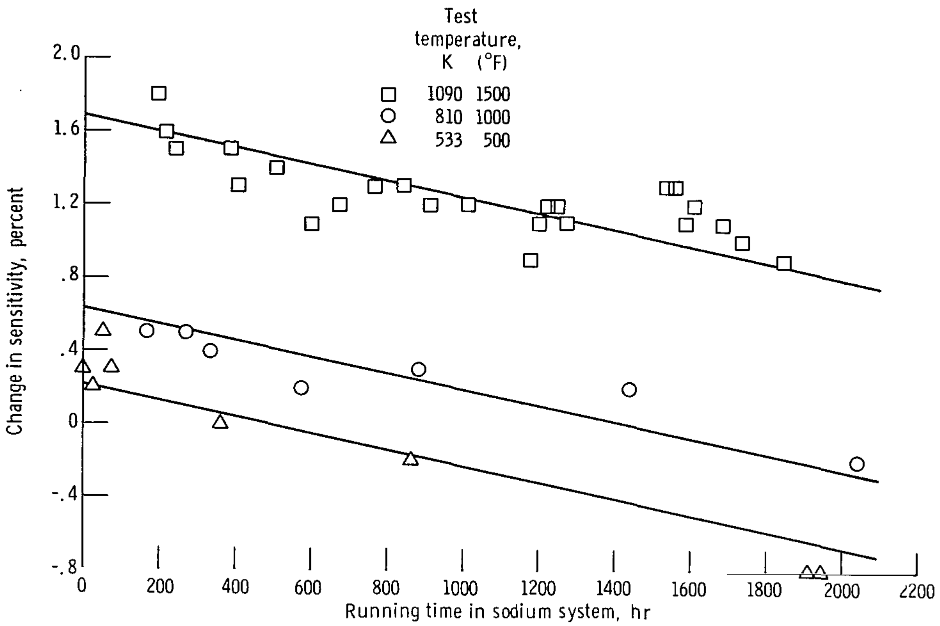


Figure 13. - Summary of calibrations from liquid-metal test.

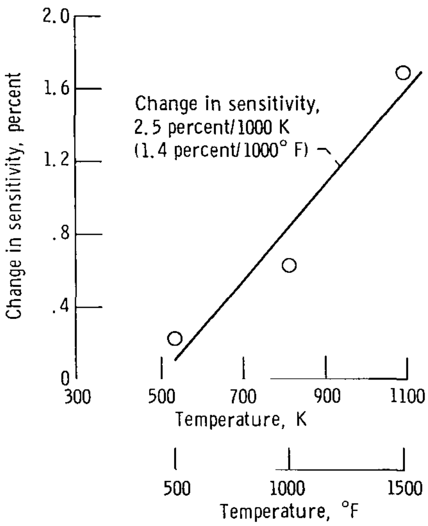


Figure 14. - Change in sensitivity as function of temperature for liquid-metal test.

## CONCLUDING REMARKS

Two pressure transducers with a range of 0 to 69 newtons per square centimeter (0 to 100 psi) were designed and tested at temperatures to 1090 K (1500° F) for periods longer than 1100 hours. Vibration tests indicated a first resonance at 2500 hertz and showed that the transducer was somewhat more sensitive to vibrations than a strain-gage-type device. The pressure sensitivity of the transducer was about 8 picocoulombs per newton per square centimeter (5.5 pC/psi) with a shift in sensitivity due to temperature of less than 3 percent per 1000 K (1.7 percent/1000° F). This change is considered to be caused mainly by thermal expansion, which increases the effective area of the sensing element. Long-term testing indicated that a shift of -0.5 percent per 1000 hours would occur in the sensitivity. This penomenon is thought to be caused by creep in the bellows convolutions that causes the effective area to decrease. The transducer should be used in installations where the vibration levels are not high and where system temperatures change slowly. When higher temperature bellows become available, the design should be suitable for constructing transducers with higher working temperatures. Overall performance indicated that the design goal of operating at 1090K (1500° F) for 1000 hours with an error of less than 3 percent at frequencies to 200 hertz was achieved.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 18, 1969,
120-27.

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